Designing Run-time Evolution for Dependable and Resilient Cyber-Physical Systems Using Digital Twins

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Montréal, Canada

MIO Transportation System

Cali, Colombia 🇨🇴

- ½ Million users per day
- 50+ bus lines
- 100s of stations / stops
- Operational plan designed to last several months: number of buses, frequency, 3 time
- Unexpected events are common
- New sensors are added over time

MIO Transportation System

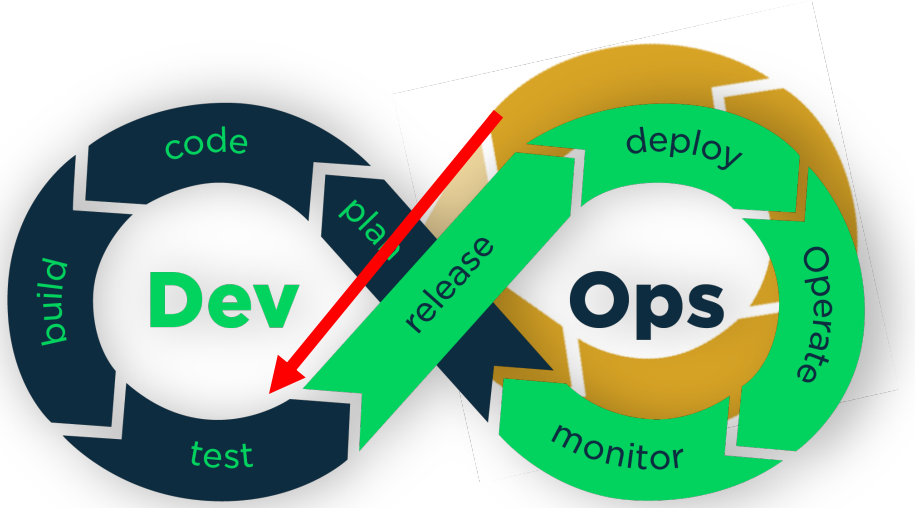
Cali, Colombia 🇨🇴

- A more frequent service
  - Lower the waiting time at each station
  - Higher cost of operation
  - More frequent maintenance

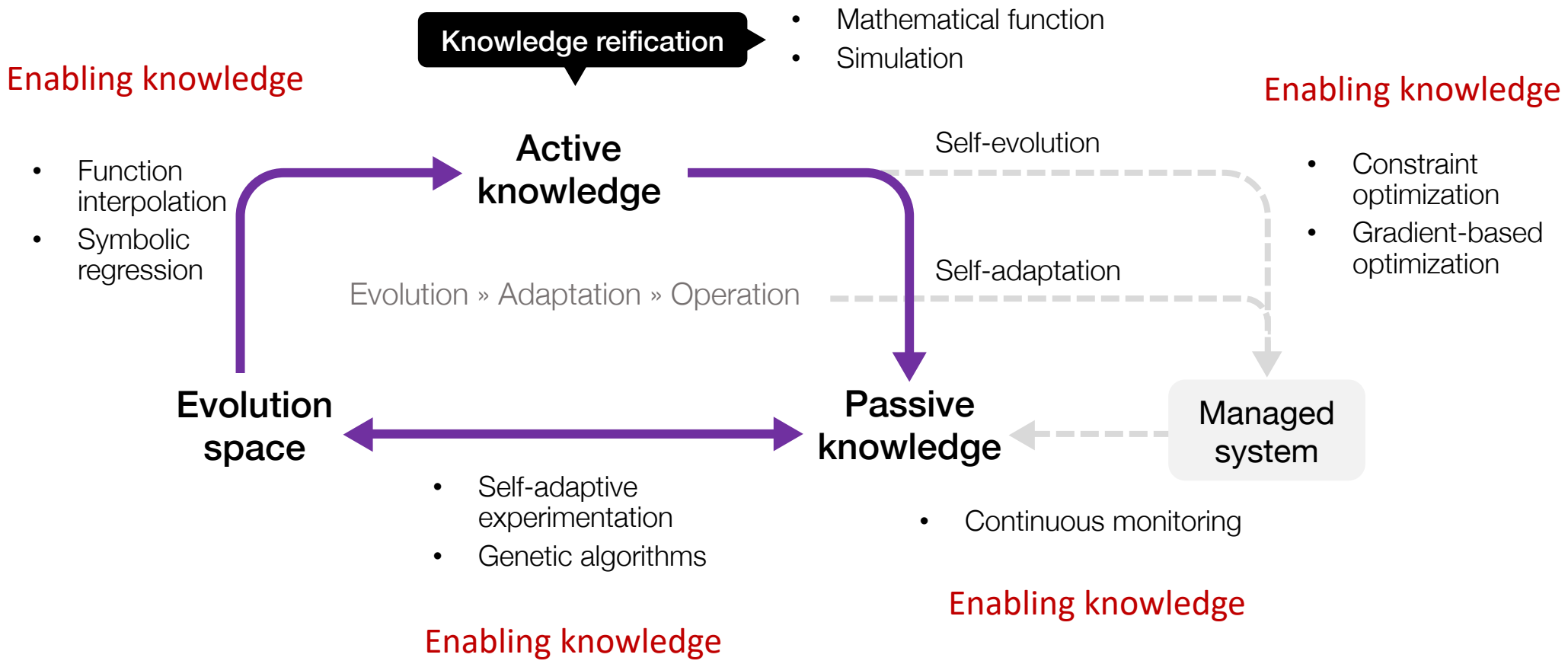
- The operations team has settled for a static plan
  - Move decision making to run-time —short and long term
  - Adaptation and evolution
  - Events vs demand change

Continuous Engineering

- Physical system ←→ Software system
- Development ←→ Operations
- Real twin ←→ Digital twin

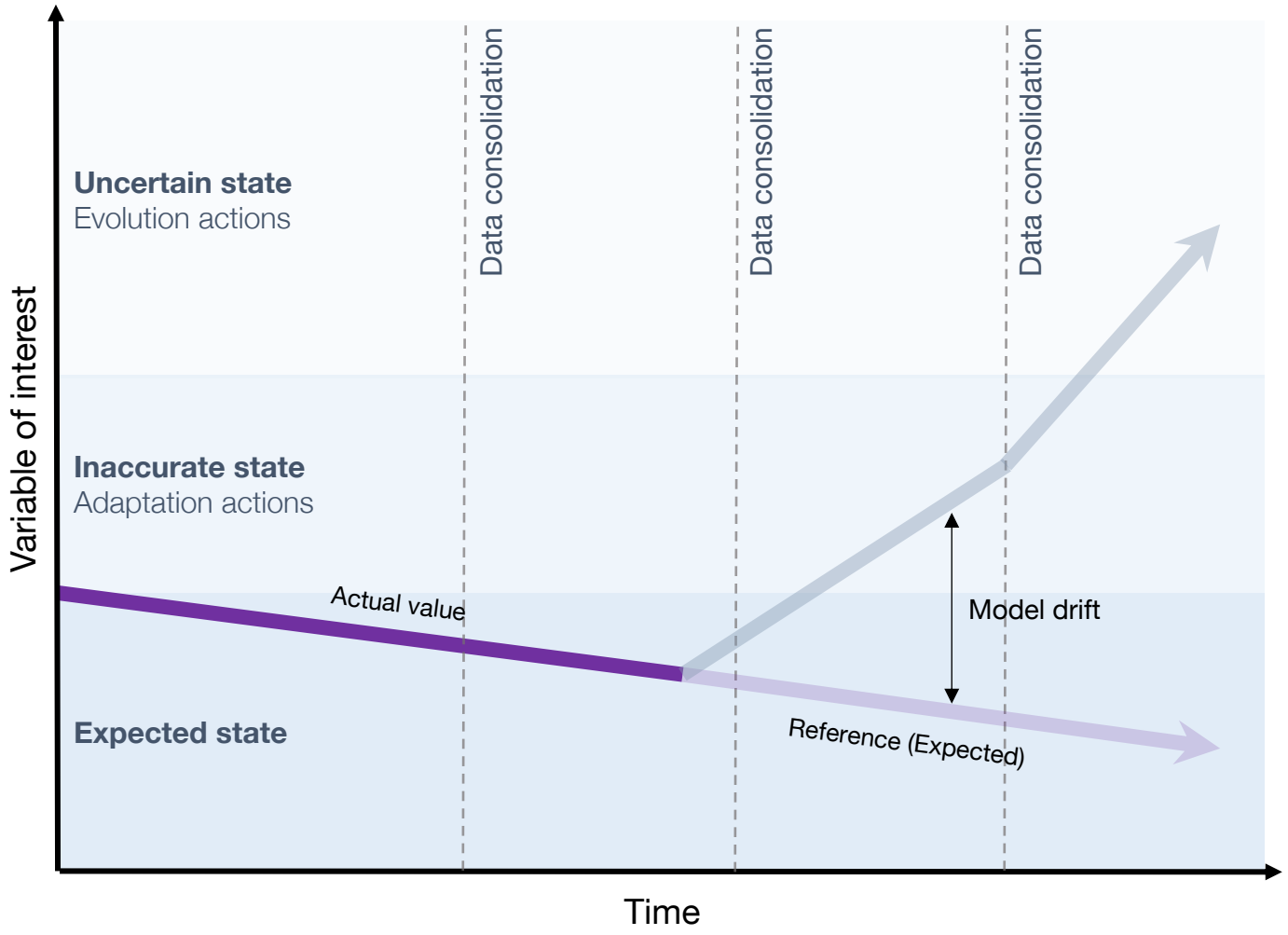


Knowledge reification



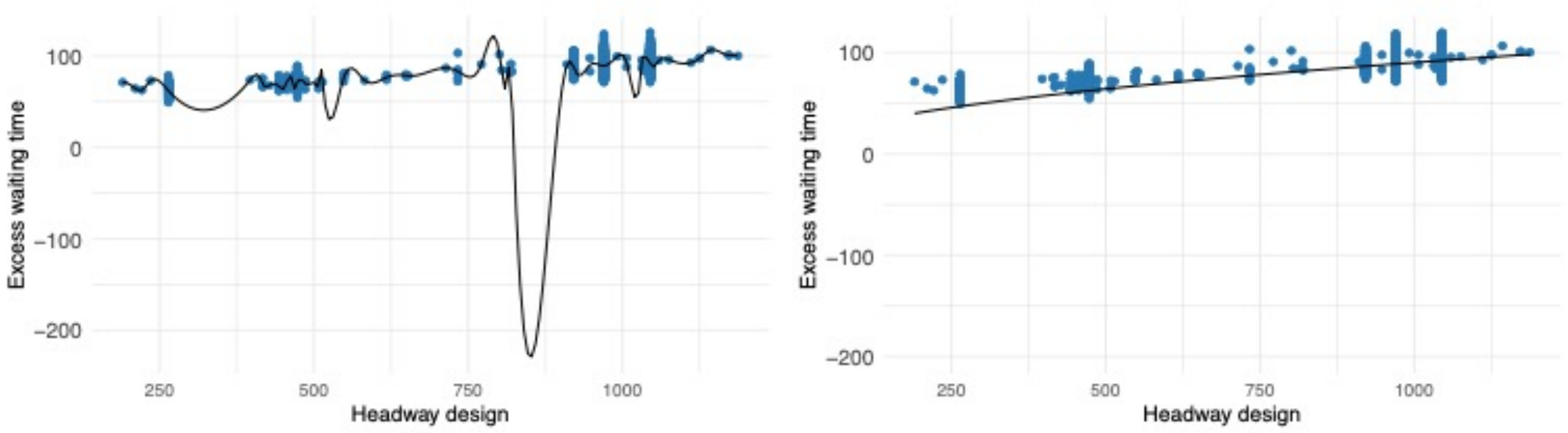
Operation » Adaptation » Evolution

- Viability zone. Usually, a single threshold
- Relationship between adaptation and evolution not clear



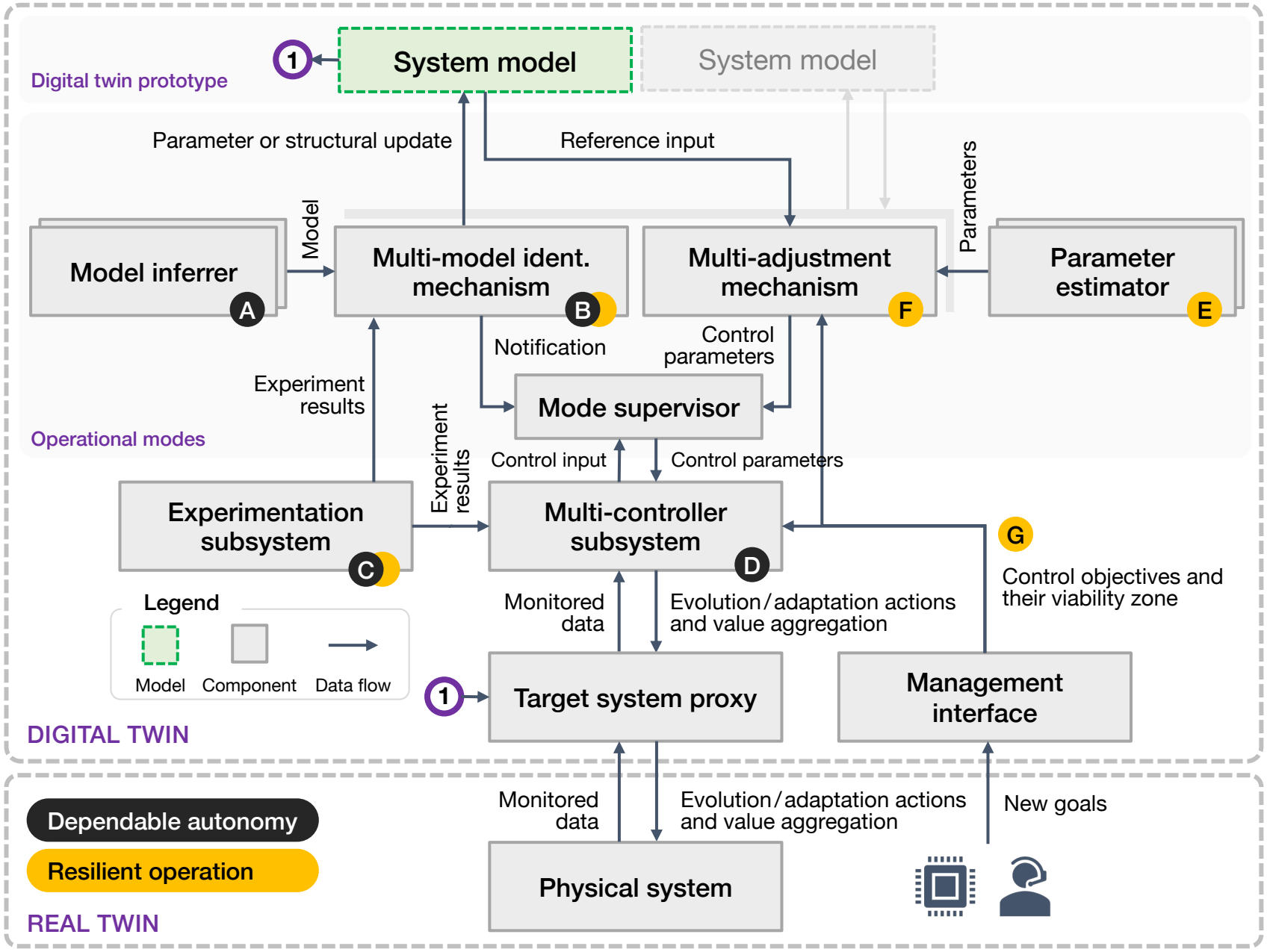
Active knowledge

- The identified model using two different techniques
- This functions can be used to predict the EWT for a given line and headway design



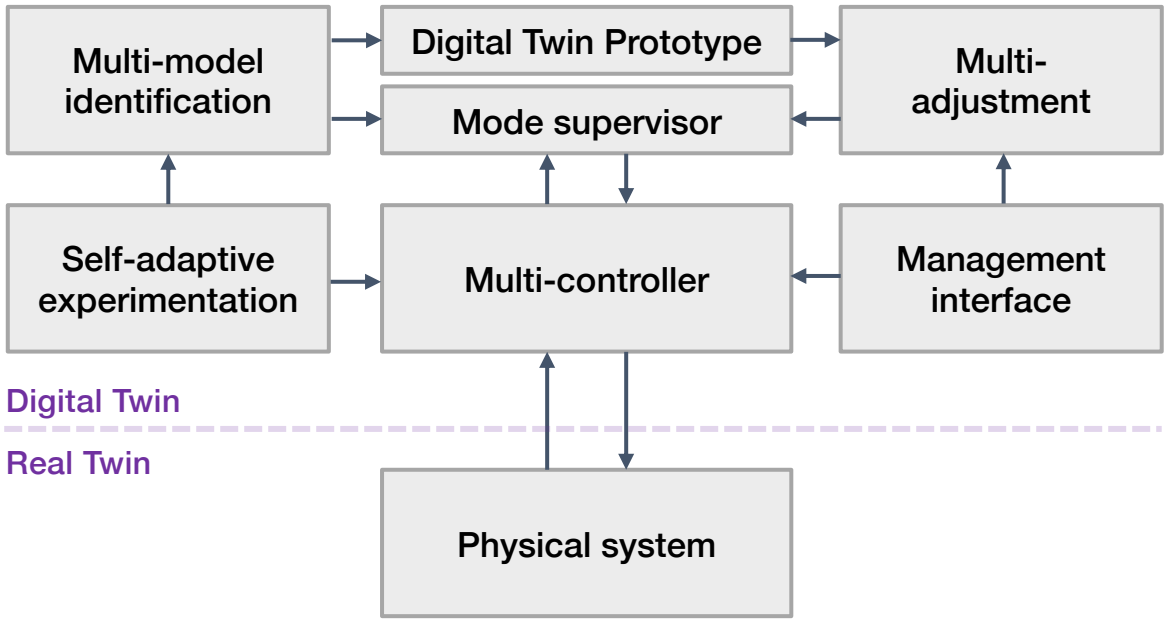
(a) Interpolated function using Natural Cubic Splines (b) Approximated function using Symbolic Regression

Fig. 20. Approximated functions



Reference Architecture

- A first step toward formalizing the evolution activities through high-level components
- Emphasizes the duality between adaptation and evolution concretely
- Features the use of multiple elements to realize a concrete task
- Integrates the concept of evolution with run-time V&V, control objectives, viability zones, run-time models



Dependable Autonomy

- Error mitigation through multi-model identification
- Reliable models through model inference
- Evidence collection through experimentation
- Autonomic behavior through adaptive control

Operational Resiliency

- Predictable adaptation through reliable models
- Run-time validation through evidence collection
- Error mitigation through parameter estimation
- Goal achievement through hyperparameter optimization
- Assurance at run-time through viability zones and control objectives

Thank you!

Take-home messages

1. Let's move from prescriptive adaptations to a run-time evolution process

2. Passive, active and **enabling** knowledge is a starting point to design smarter systems

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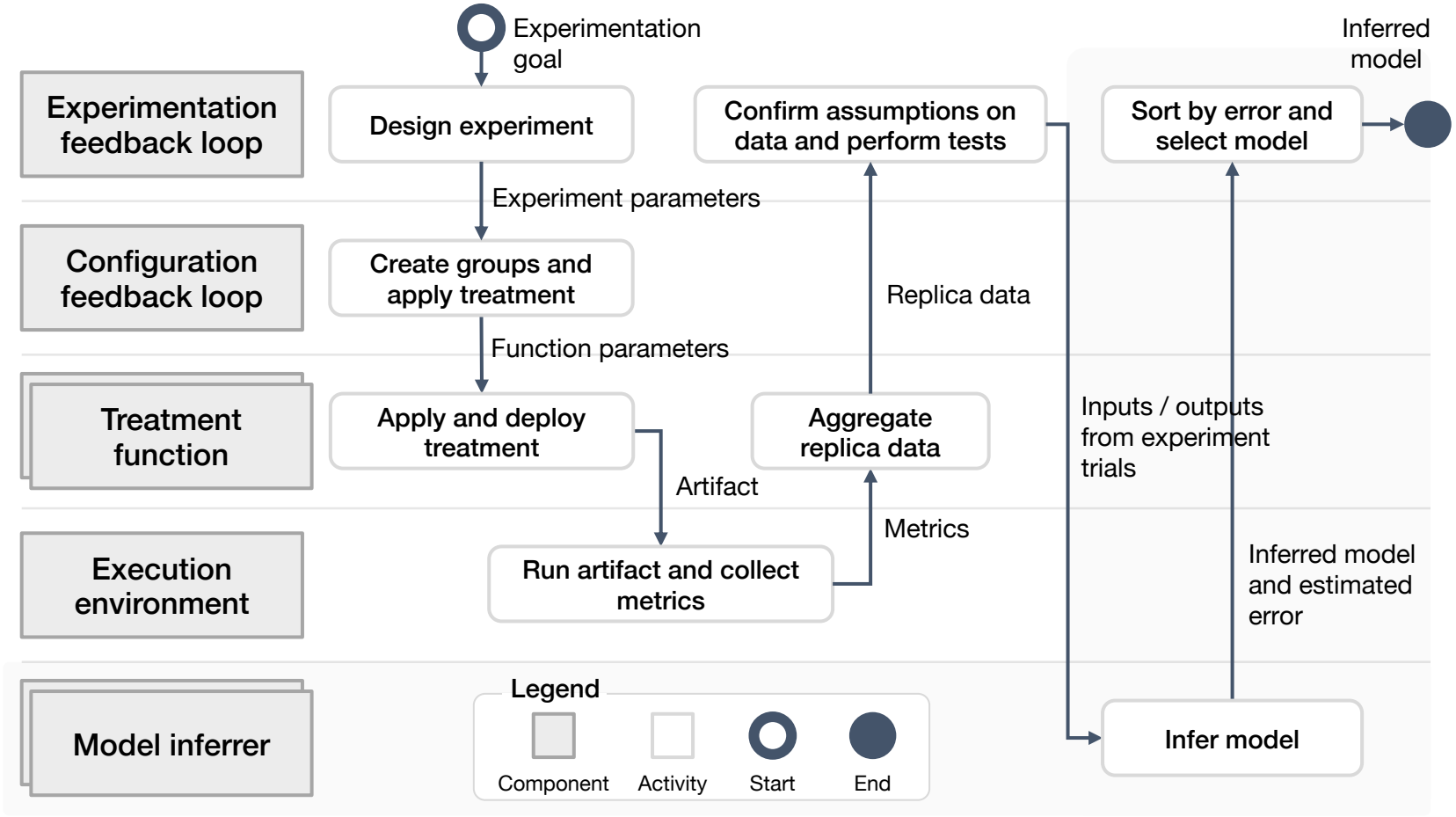
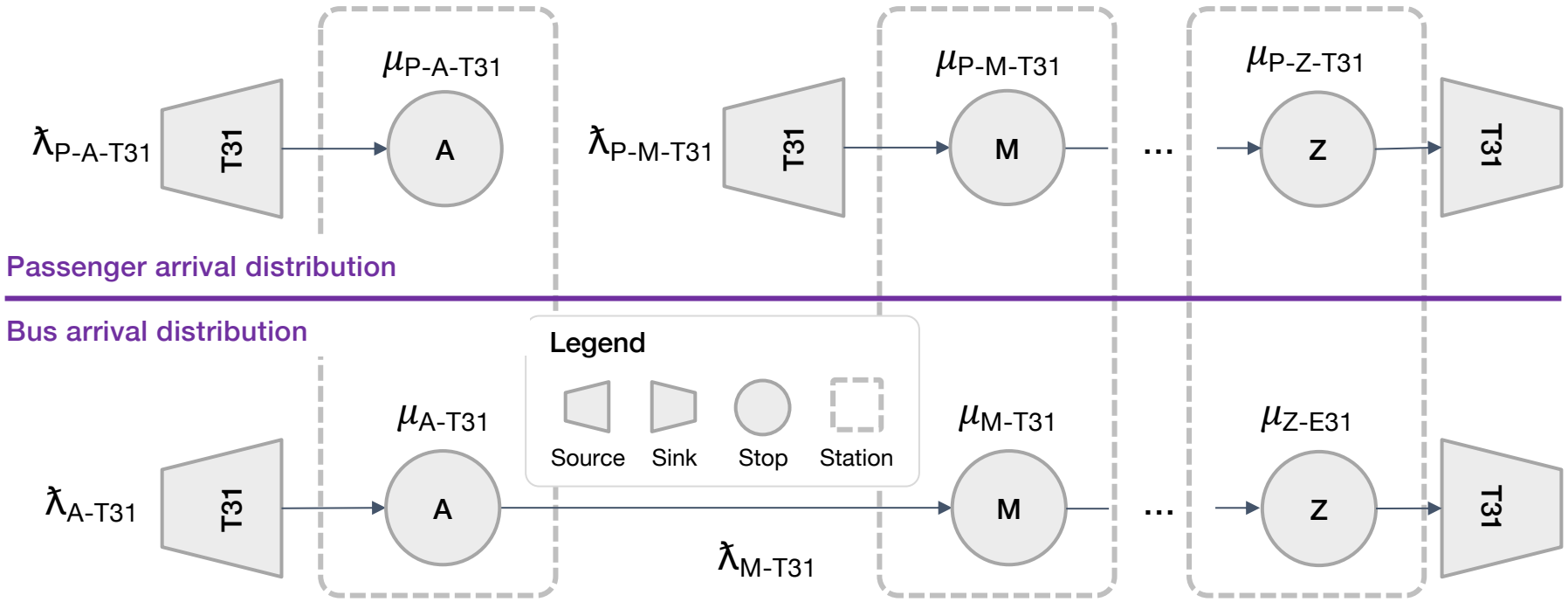
Multi-model identification mechanism

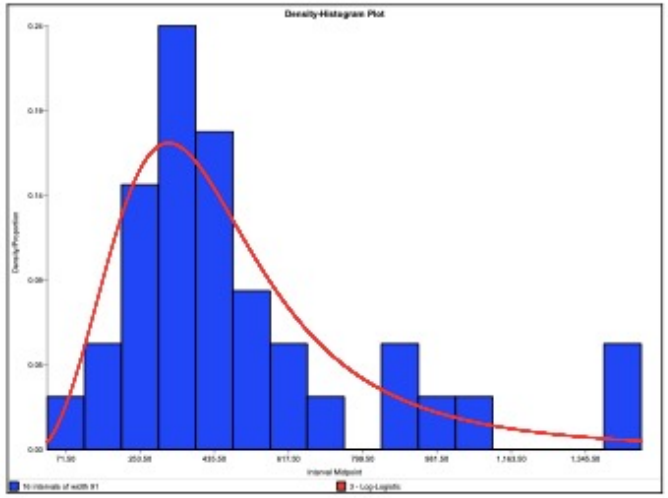


DTP-conforming Digital Twin Instance

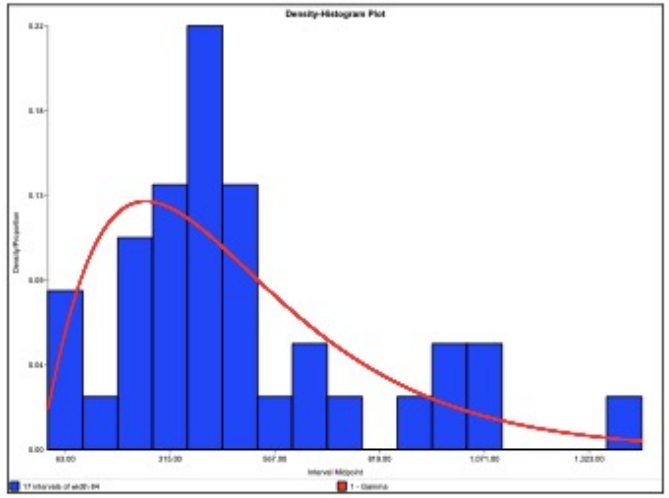


Bus interarrival times

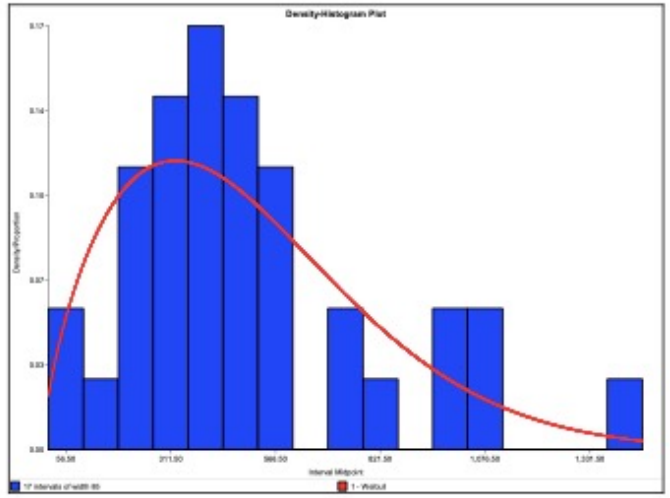
- Distribution of interarrival times for buses at 3 stations



(a) Bus interarrival times for CHA2



(b) Bus interarrival times for FIA1

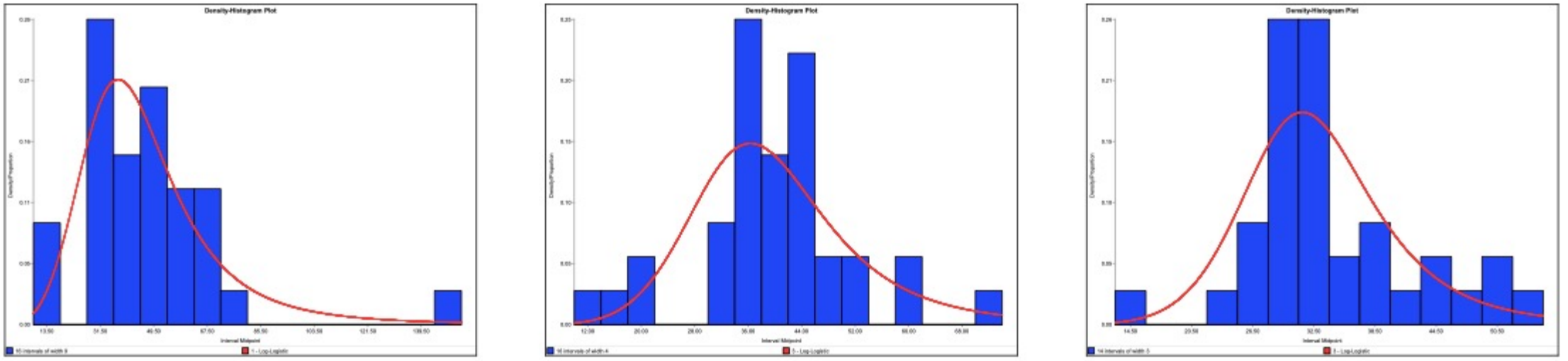


(c) Bus interarrival times for SAA1

Fig. 13. Density-histogram plots for reference bus interarrival times

Service times

- Distributions of service times for a bus line at 3 stations

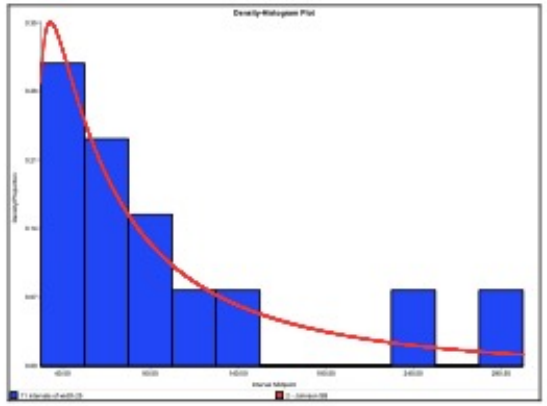


(a) Service times for CHA2 (b) Service times for FIA1 (c) Service times for SAA1

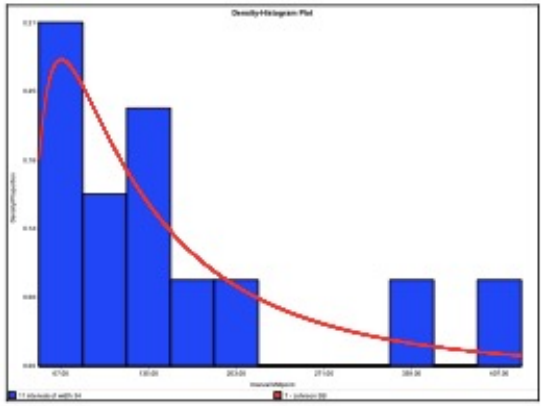
Fig. 14. Density-histogram plots for reference service times

Passenger interarrival times

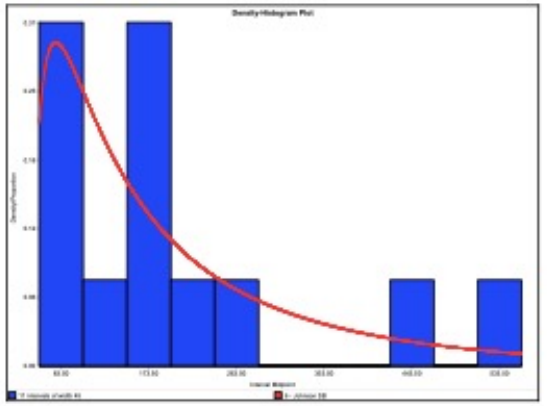
- Distributions of passenger interarrival times at 4 stops



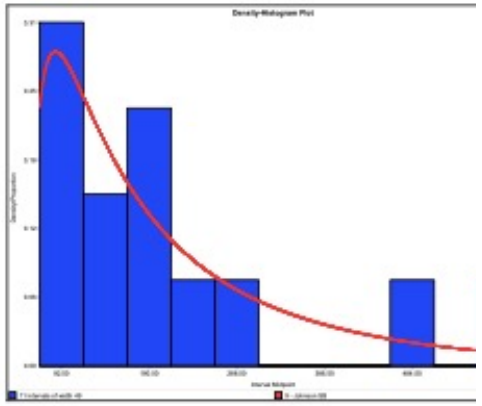
(a) Passenger interarrival times for PCA2



(b) Passenger interarrival times for CHA2



(c) Passenger interarrival times for FIA1

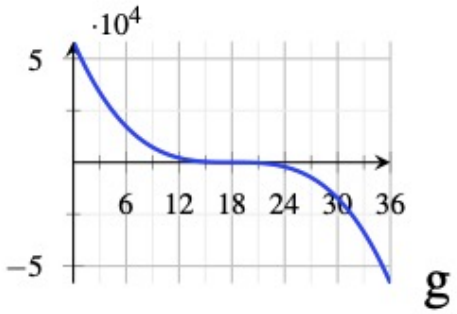


(d) Passenger interarri times for SAA1

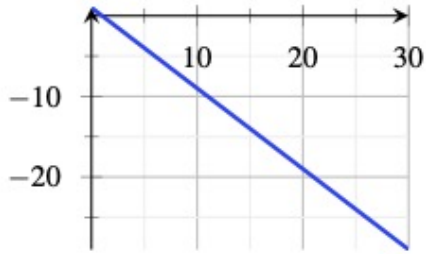
Fig. 15. Density-histogram plots for reference passenger interarrival times

Components of fitness function

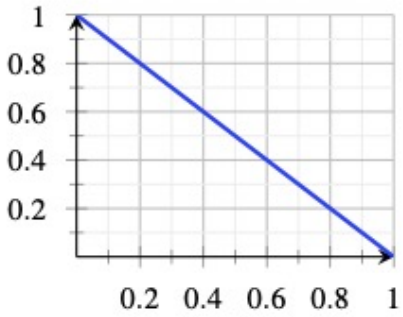
- 4 functions are used to optimize the use of resources
- Parameters include number of buses, planned number of buses, observed headway, HCoV, EWT



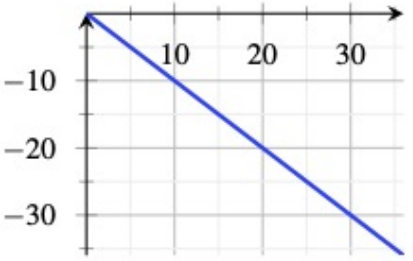
(a) Cubic function



(b) Normalized function (before normalization)



(c) Normalized function

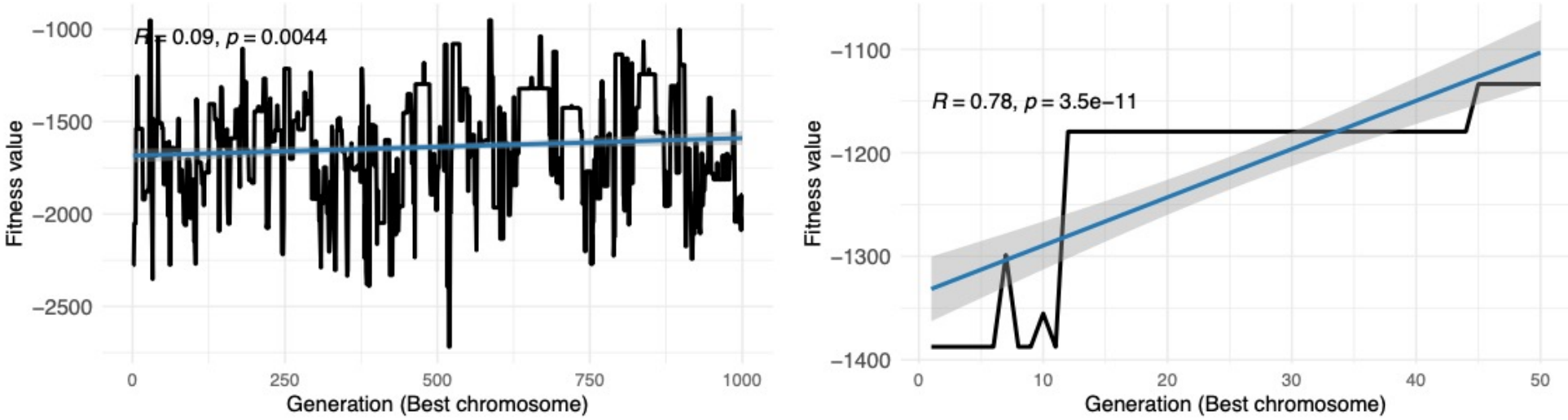


(d) Linear function

Fig. 17. Components of the fitness function

Evolution space exploration

- A genetic algorithm explores the solution space using the (dynamic) simulation model
- The algorithm can be used to find a good solution too



(a) Exploration mode

(b) Optimization mode

Fig. 18. Overall fitness performance over time

Evolution space exploration

- Measured outputs based on the simulated scenarios (solution space exploration)

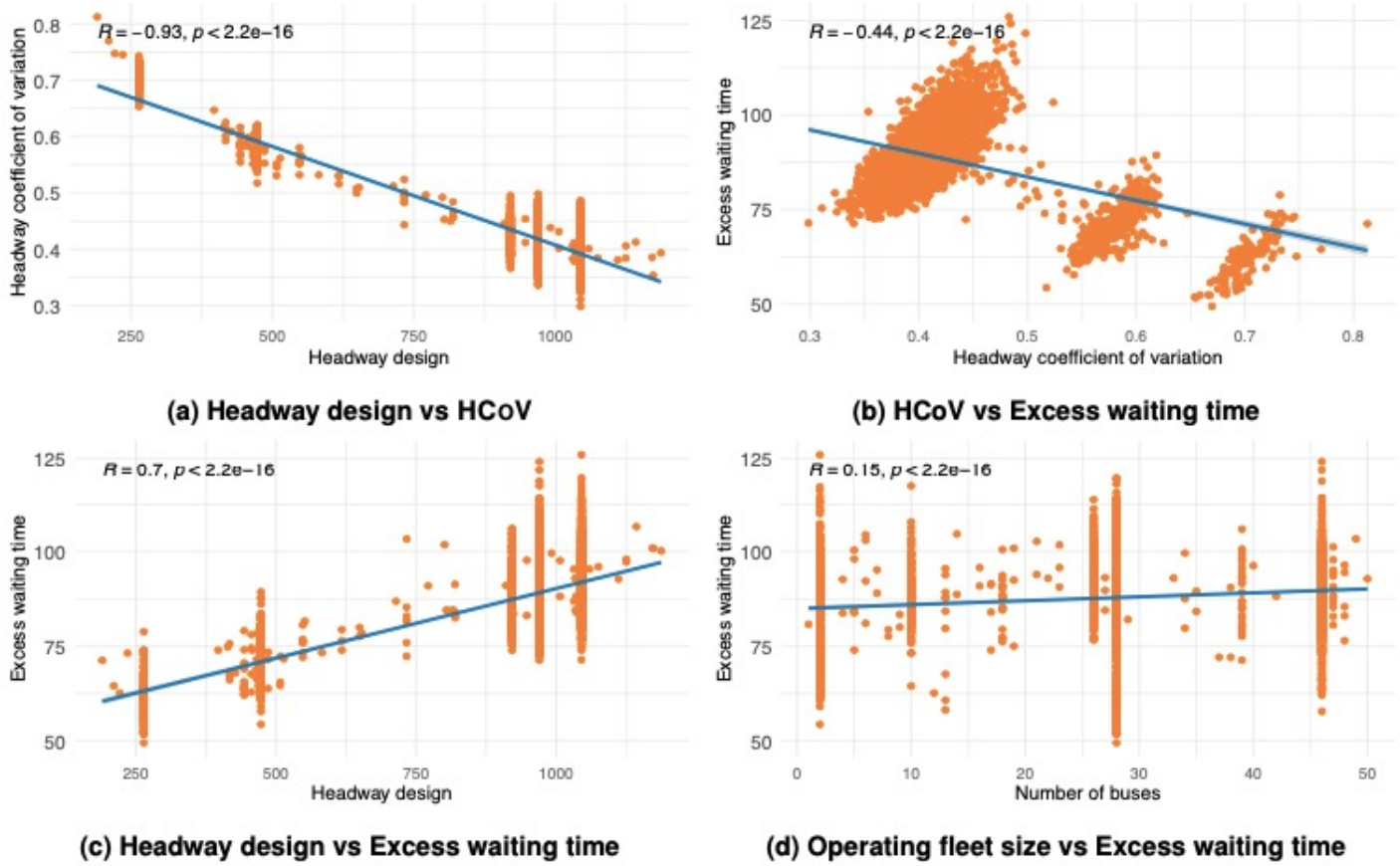


Fig. 19. Correlation and behavior of independent variables and measured metrics with respect to the excess waiting time